Optical Burst Switching: Benefits and Challenges

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ABSTRACT

This paper discusses the emerging area of Optical Burst Switching (OBS), examining its potential benefits for future optical/data network implementations. We develop insights into various performance metrics for OBS such as the resiliency (i.e., failure recovery), bandwidth/resource efficiency and overall economic advantages. The quantification of resiliency/efficiency metrics depends on the considerations such as Burst Wavelength Conversion (BWC), connection characteristics, burst properties and network-wide statistical traffic multiplexing. We quantify the bandwidth or wavelength savings for OBS architectures with/without BWC as a function of the wavelength fill, burst overheads and burstiness of the underlying traffic. We also examine issues that can help or impede technology evolution for implementation of OBS. These issues include BWC, optical power management for bursts, and graceful addition and deletion of bursts into optical wavelength channels.

Keywords: OBS, Optical Burst Switching, Performance, Statistical Multiplexing, Wavelength Gain

1. INTRODUCTION

There is growing interest in Optical Burst Switching (OBS), which is conceptually aimed at the benefits of packet switching but without the need for O-E-O (Optical to Electrical to Optical) conversion at intermediate switching nodes.[2–5] In this paper, we discuss this emerging technology, highlighting its potential benefits for future optical/data network implementations as well as many associated challenges that lie ahead. If successfully developed and deployed, OBS would provide the combined capabilities of connection switching and statistical multiplexing at the optical layer across the core network nodes. This could result in significant resource (bandwidth, wavelengths, regenerators, port count) savings. It can also yield more economical implementation of core networks as compared to what can be done with existing technology, which is based on statistical multiplexing and routing at the MPLS/IP layer and wavelength-connection switching at the optical layer. Showing that OBS is indeed economical, flexible and resilient would build a strong case for implementation of new types of networks, and hasten the deployment of new types of services that can take advantage of the increased available bandwidth.

As OBS technology matures, its principal benefits for the core network are the following:

- **Connection Add/Drop at Optical Layer with Finer Bandwidth Granularity:** OBS will result in superior utilization of Ultra Long Haul Reach (ULHR) fiber transmission lines. Optical wavelength channels do not have to be terminated prematurely (i.e., at shorter distances than the full reach) merely for connection add/drop purposes. OBS is expected to allow connection add/drop with finer bandwidth granularity in the optical layer. The add/drop operation can be potentially engineered at the burst layer in such a way that it remains practically transparent to traffic that is passed through. Edge routers present the IP/MPLS traffic to the OBS node, and the OBS node further multiplexes/de-multiplexes the traffic from multiple edge routers as they ingress/egress from the core network.
- **Bandwidth Savings and Lower IP/MPLS Routing Cost:** OBS will allow statistical traffic multiplexing, routing and switching at the optical layer at core network nodes, which can result in use of much fewer core IP/MPLS router ports and hence it could save the network costs significantly. Each wavelength in the OBS network can carry much multiplexed traffic, and the bandwidth can be much better utilized by the underlying IP/MPLS packet traffic.

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- **Regenerator Cost Savings:** The number of Optical-Electrical-Optical (OEO) conversions would be significantly reduced in an OBS network for the actual applications traffic. The use of OEO will still be required for signaling traffic at each node; such traffic is likely to traverse the network on separate Optical Supervisory Channels (OSCs). With fewer OEO conversions for the applications traffic, the regenerator (i.e., OEO) cost component should be significantly reduced for OBS as compared to the existing core network implementations.

- **Resiliency:** A burst-multiplexed connection can be Variable Bit-Rate (VBR) or Constant Bit-Rate (CBR). Each connection (CBR or VBR) can be provided with 1+1 or 1:1 protection. Fewer extra resources should be needed for protection, as compared to existing core network implementations, because of the higher bandwidth efficiency. Higher bandwidth efficiency results in lower connection lengths and hence usage of fewer regenerators and wavelength conversions. Various deflection routing techniques for contention resolution as well as protection have been proposed and at least some of them seem quite promising.[16–23]

In this paper, we develop insights into the resiliency (i.e., connection continuity or recovery from fault occurrence), bandwidth/resource efficiency and overall economic advantages of OBS. The quantification of resiliency/efficiency metrics depends on the considerations such as use of Burst Wavelength Conversion (BWC), connection characteristics, burst properties and network-wide statistical traffic multiplexing. We quantify the bandwidth or wavelength savings for OBS with/without BWC as a function of the wavelength fill, burst overheads and burstiness of the underlying traffic. We show that OBS is architecturally very attractive if the traffic is bursty, i.e., if bandwidth usage in a typical wavelength channel is sporadic with low channel fill and a high ratio of peak to average payload data rates. However, in practice some services require sustained fixed bandwidth (e.g., full OC192) channel allocation, and to accommodate such cases OBS should have the added feature of operating in a hybrid mode (i.e., combination of full wavelength connections and statistical burst switching/multiplexing). Full wavelength connections in this case are dedicated pipes as opposed to very long bursts. We also examine issues that can help or impede technology evolution for implementation of OBS. These issues include BWC, optical power management for bursts, and graceful addition and deletion of bursts into optical wavelength channels.[6, 11–13]

2. OBS NETWORK CONTROL AND BURST FORWARDING METHODS

The basic switching technology needed for implementation of burst switching seems to be maturing but all the pieces of the puzzle are far from coming together at this time. Optical phased array technology[14, 15] is promising in terms of the basic operation of a burst switching fabric, but control and burst handling techniques still need significant consideration and effort.

The basic architecture of an OBS network would be a network of OBS core switches as shown in Figure 1. The OBS switches are connected to edge network elements such as routers (IP/MPLS), Digital Subscriber Loop Access Multiplexers (DSLAM) for access over DSL networks, and Cable Modem Termination Systems (CMTS) for access over HFC networks. The OBS nodes have burst switching, Dense Wavelength Division Multiplexing (DWDM) and (desirably) tunable laser capabilities. One wavelength on each link is reserved for the Optical Supervisory Channel (OSC). The OSC carries control packets that contain information pertaining to burst timing, destination, length, and other information. The Signaling and Control Processor (SCP) performs the control functions that include processing the signaling and control messages. The SCP performs other control functions such as distributed routing, neighbor discovery, connection setup, maintenance, query and teardown, and fault recovery.

Each burst is typically composed of multiple IP packets. The OBS network is based on elements that perform the following functions: adaptation of IP traffic to a burst format, burst switching, DWDM, Burst Wavelength Conversion (BWC) using fast tunable lasers, TDM, and processing control packets (in the SCP). The OBS switches multiplex and demultiplex the optical bursts over wavelength channels that span the underlying DWDM transport network.

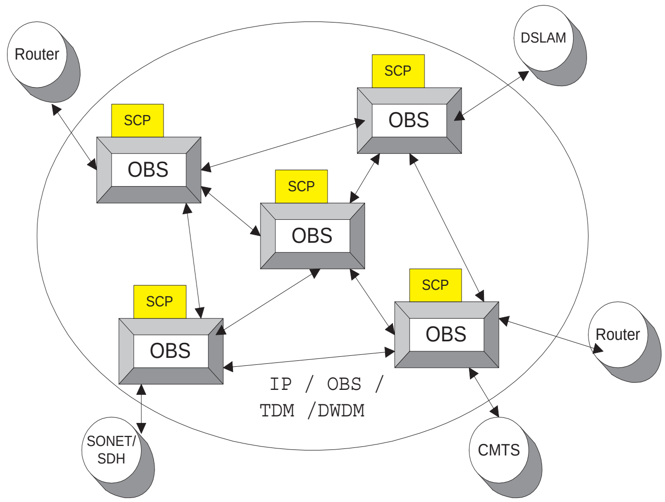

Figure 1. Basic architecture of an OBS network

2.1. Optical Supervisory Channel and Control Packets

A control packet is associated with each burst. It carries information pertaining to the destination address, burst size, timing, etc. If the control packets traverse the same wavelength channel as the optical bursts, then a regenerator (O-E-O conversion) is mandated for each of the optical channels or wavelengths. However, in reality the architecture would require the control packets to traverse a separate OSC (optical supervisory channel with OC12 or OC48 bandwidth) on a wavelength set aside on each fiber in the network. In that case, the regenerator is not mandated for each wavelength that is used for the application traffic. The regenerator will be used, in that case, for only the wavelengths that need restoration of optical signal quality. The OSC channel will always go through a regenerator at each node because the control packets must be processed in order to manage burst routing and scheduling. Sending control traffic in the OSCs (out-of-band) is preferable because the cost of regenerators is high. However, there is a risk that the behavior of the control packets becomes very asynchronous, and the time coordination between the control packets and the bursts can become a very tricky and challenging issue. If some bursts are buffered using Fiber Delay Lines (FDLs) for contention resolution on the wavelength channels, then there is also the task (typically performed in the SCP) of updating the associated control packets so that the burst timing information is appropriately modified to reflect the incremental delay due to FDL buffering. The updated burst timing information would be required for accurate burst scheduling at the downstream nodes. If deflection routing (described in a later section) is used for contention resolution or protection, then the control packets also need to be appropriately redirected along the alternate route that is associated with deflection routing.

2.2. OBS Burst Forwarding Methods

Optical burst switching can be implemented in different architectural frameworks vis-a-vis burst switching/ forwarding and buffering arrangements. These include (1) Burst reservation, (2) Burst cut-through, and (3) Burst store and forward. Also, the use of Deflection Routing and FDL add additional dimensions to the burst switching/ forwarding methods.

Burst Reservation: In the burst reservation scheme, the control packet goes ahead to each node along the path, the resources are reserved ahead of the burst arrival at each transit node, and the burst is transmitted after an acknowledgement is received at the ingress node from the egress node. Burst contention is avoided by reserving the required time for burst transmission on each link along the route.

Burst Cut-Through: In the burst cut-through method, a burst immediately follows the control packet on each hop of the path in its own wavelength channel. The control packet must be processed quickly enough at each node so that it always stays ahead of the associated burst. In the event of contention at a node for transmission

Table 1. OBS architectural alternatives vis-a-vis switching and buffering choices

OBS Buffering Method → OBS Switching Method ↓	Use only packet buffering at edge nodes; no buffering at transit nodes	Additionally, optical buffering for bursts at transit OBS nodes
Burst reservation end-to-end	Burst contentions are avoided by prior reservations of wavelength and transmission time slot. This is done end-to-end for each burst individually.	N/A
Burst cut-through with blocking	Entire burst gets dropped if there is contention; Egress node retransmits lost burst.	N/A
Burst cut-through with clipping	Portion of the burst gets clipped at front end if there is contention; Application layer will retransmit lost packets.	N/A
Burst cut-through with deflection routing	Burst gets routed instantaneously on an alternate egress link if there is contention.	N/A
Burst store and forward	N/A	Bursts are stored in FDL buffers at each transit node; contention is avoided but bursts can get dropped if buffers are full.
Burst store and forward and deflection routing	N/A	Bursts are stored in FDL buffers at each transit node and are deflection routed to further avoid contention; with a smaller probability bursts can still get dropped if buffers are full.

on the desired link, Deflection Routing (DR) may be employed. If that does not resolve the contention, then retransmission from the source node would be used for that burst.

Burst Store and Forward: In the burst store-and-forward method, Fiber Delay-Line (FDL) buffering is provided at each node. The burst can be entirely or partially stored at each OBS node before it is forwarded to the next node in order to mitigate contention and burst dropping. This method allows the burst to arrive at a node without prior reservation, and FDL buffering is used if it can't be scheduled immediately for forwarding. Additionally, deflection routing can be used to further help resolve any contention.

2.2.1. Matrix of Architectural Alternatives

Table 1 illustrates the various OBS architectural alternatives in terms of the burst handling techniques and the possible use of fiber delay-line for buffering and contention resolution. It is a summary of the techniques described above. In addition to the burst forwarding principle summarized in Table 1, several burst scheduling protocols have been proposed to implement OBS considering both wavelength and timeslot assignments. Examples of such protocols are Just Enough Time (JET), Just-In Time (JIT), etc.[3, 18, 25, 27] and they are commonly applicable to many of the burst forwarding techniques in Table 1.

2.2.2. Buffer Directionality

FDL buffering may or may be used in OBS depending on the cost and ease of implementation. Also, it is possible that the FDL buffering can only be directional, i.e., one input/output port cannot share the buffers with other input/output ports. In such a case, the contention mitigation advantage of fiber delay-line buffering becomes restrictive. However, if the buffers can be fully shared across all input/output ports in the OBS switch, then the buffers provide much superior contention mitigation performance (i.e., lower burst loss).

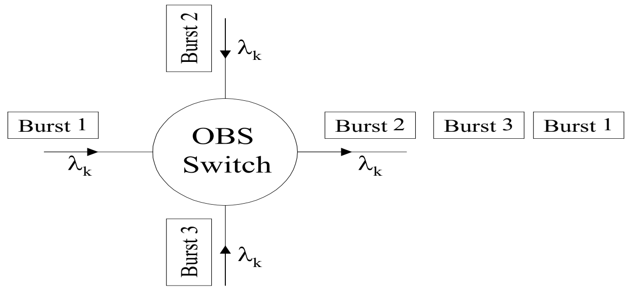

Figure 2. OBS with uniform wavelength multiplexing requirement

3. STATISTICAL MULTIPLEXING GAIN AT BURST LAYER AND SCALABILITY

3.1. OBS With and Without Burst Wavelength Conversion

In the 4×4 OBS node example shown in Figure 2, there are four fiber ports each carrying many wavelengths. The current technology may require that incoming bursts arriving on a wavelengths λ_k on an ingress fiber can be multiplexed only onto the same wavelength λ_k on any of the egress fibers. This is a possibility and we call it the wavelength continuity constraint. Due to this restriction, the multiplexing gain will be limited, i.e., lower compared to the case when such restriction may not apply. The wavelength λ_k on the egress fiber will be underutilized and the advantage of statistical multiplexing is reduced. However, the requirement of wavelength continuity would go away with the use of fast tunable lasers,[7–10, 28] provided that the same can be accomplished in the near future in OBS switches. Fast tunable lasers would facilitate burst wavelength conversions on a burst-by-burst basis. We distinguish between OBS architectures with and without Burst Wavelength Conversion (BWC) as follows. In the OBS architecture without BWC, the uniform wavelength requirement (see Figure 2) is applied. In the OBS architecture without BWC, an incoming burst on any fiber and any wavelength can be multiplexed onto any outgoing wavelength using fast tunable lasers on the OBS switch egress ports. In Section 6, we will quantitatively compare the bandwidth or wavelength channel gain for OBS with/without BWC relative to GMPLS.

3.2. Sensitivity to Burst Overhead

In an OBS network, burst overhead results from the need to provide temporal guard bands between bursts. The size of these guard-bands is critical to economic and bandwidth-efficiency benefits associated with OBS. The main argument for OBS would be for bandwidth efficiency and cost savings (e.g., need to light up much fewer wavelengths in a fiber). Traffic from many sources can be multiplexed and demultiplexed with ease, and thereby the need for a dedicated wavelength channel for each source-destination pair is obviated. If the typical bandwidth utilization in a wavelength is about 10% (e.g., due to the sporadic nature of IP traffic) but the guard bands are so large that they consume 80% of the overall bandwidth, then the economics of OBS would be unattractive. However, if the guard bands cause only 10% or 20% overhead, then OBS would be significantly bandwidth efficient and economical. We need to understand and quantify the effects of the temporal guard-band. As an example, it has been shown that for an OBS switch with 400B fixed size bursts ("chunks"), the overall guard-band and switching overhead in the burst switching fabric is approximately 20%.[15] There are likely to be additional temporal guard-bands associated with the use of tunable lasers for burst wavelength conversions. In the simulation results section of this paper, we provide some numerical examples showing the effects of guard-band overheads on the bandwidth efficiency of OBS.

3.3. Fixed Versus Variable Size Bursts and Burst Assembly Techniques

Variable size bursts can be more economical from a bandwidth efficiency point of view. But fixed size bursts can be potentially favored for ease of implementation. One known implementation of a burst switching fabric based on optical phased arrays has fixed (400 B) size bursts for a line rate of 12.5 Gbps.[15] In this case, a synchronous switching scheme was used with padding/segmentation to ensure that all bursts passing through the switch had the same length. One can study the issue of optimal burst size considering several constraints such as temporal guard-band requirements, implementation complexity of variable size bursts, traffic flow patterns, etc. The latter refers to the ability of collecting enough packets destined toward the same egress node/port so that a burst of certain (fixed) size can be efficiently packed; otherwise it may be underutilized (note: unused space is usually filled with padding bytes).

Several authors have examined burst assembly design issues in detail.[31–34] A recent paper[32] developed a simple burst assembly algorithm that relies on timers for the outgoing packet queues at the OBS network's edge nodes. Each node maintains a separate queue for each destination; when a packet enters an empty queue a timer is started. Packets accumulate until the timer reaches a threshold value at which point the queue's contents are formed into a burst and sent out. If the burst is smaller than a desired minimum size it is padded so that it has exactly the minimum duration. This approach produces bursts that are longer than some desired minimum but whose maximum delay is held to a fixed threshold. It has the added benefit of reducing the self-similarity in the traffic generated by the sources, which improves the core network's queueing performance.

Several authors have explored more sophisticated burst assembly and scheduling algorithms. Burst assembly for QoS support[34] uses a priority-based contention resolution scheme in which low-priority bursts' tails are dropped if a higher-priority burst needs to use the output port that was originally assigned to the lower-priority burst. In this method, a low-priority burst is dropped in its entirety if a burst with higher priority is already using the output port. The authors also propose a general burst assembly scheme that allows packets of various classes to be assembled into bursts of various types, to which different burst priorities are assigned. The assembly scheme supports the creation of single-class bursts or composite-class bursts (i.e. bursts composed of packets of different classes). Composite bursts are constructed so that lower-priority packets are toward the tail and thus they can be dropped with higher probability if a conflict with a higher-priority burst occurs. Simulations performed by the authors indicate that composite assembly provides greater QoS differentiation without significantly penalizing the lower-priority classes.

3.4. Scaling of the Signaling and Control Processor (SCP) and OSC Bandwidth

The control packets and signaling messages are processed in a Signaling and Control Processor (SCP). Sizing the SCP for required processing power and buffer capacity is another important area of study for an OBS network design. It is necessary to quantify the scalability of the SCP as function of growing network size and traffic granularity. In essence the bursts for VBR traffic would need to be treated individually and would have one control packet associated with each burst. However, for the CBR traffic it should be possible to have a set of control packets per CBR flow rather than one control packet per burst. Thus the VBR traffic causes higher control traffic load on the SCP as compared to CBR traffic. If the VBR bursts can be scheduled in groups via a single control packet per group, then the traffic granularity is coarser, resulting in lower load on the SCP. So the SCP sizing is a function of the network size, traffic mix and granularity. Possibility of loss of control packets and concomitant optical burst losses due to SCP saturation should be characterized, and both should be kept to a minimum by design. In addition to the SCP, the OSC channel bandwidth also needs to be similarly sized and understood for scalability requirements.

4. PROTECTION AND RESTORATION

4.1. 1+1 Protection Scheme

For 1+1 protection in OBS networks, we can consider an extension of the diversity routing approach originally proposed by Maxemchuk in 1975, and extended by Nagarajan et al[29] for use with MPLS label switched networks. In this approach, packets are duplicated at the network ingress and assigned serial numbers and routed over two disjoint paths toward their destination. A sliding window that moves over a predetermined sequence number space is used at the network egress to discard excess copies of the duplicated packets. The benefit of this approach is that packet transmission can continue without disruption in the event of a failure on either of the two paths. A similar approach can be deployed in a fairly direct fashion in OBS networks. Sequence numbers would be used either in the headers of the frames that compose the burst, or within the control packet itself. Griffith and Lee[1] have examined issues related to 1+1 protection in OBS, particularly the effect of differences in the propagation delays on the two paths.

Also, resources in the OBS networks can be reserved and signaled for use when needed for other methods of protection such as 1:1, 1:N, etc. Any of these, including the 1+1 protection with burst level diversity routing, can be used in conjunction with deflection routing described below.

4.2. Restoration Using Deflection Routing and Source Retransmission

The restoration mechanism involves a combination of using deflection routing to respond to failures in OBS networks.[16] Deflection routing is commonly proposed as a mechanism for contention mitigation at OBS nodes. If a burst associated with incoming control packet cannot be scheduled at the desired time, the node will, rather than dropping the burst, attempt to forward it to the destination via an alternate route. Typically, each node maintains an alternate route to each destination point in the network in a database. Presumably a node that is immediately upstream from a failure will have some protocol for routing bursts around the failure rather than dropping them. In such case, it is best to avoid buffering every burst that arrives while the downstream link is in a failed state. We propose using signaling to notify the upstream node of the failure condition so that it may modify the route associated with the existing burst session. In addition, the node that is upstream of the failure point will have to be made to recognize the deflection route as the new primary route. Upon repair of the downstream node, the upstream node is notified and the rerouted burst flows are reverted to their original routes via the downstream node.

4.3. Protection Vs. Connection-Blocking Trade-Off

There is an inherent trade-off between protection (resilience) and connection blocking. When protection in any form (1+1, 1:1, 1:n, etc.) is provided, more network resources (wavelengths, regenerators) are committed. Then, as the traffic on the network grows, either more resources have to be commissioned or the blocking of new connection would occur. In other words, the requirement of protection causes network resources to be exhausted sooner as traffic grows. However, with OBS it is possible to use network resources far more economically. The statistical multiplexing advantage of OBS allows both wavelengths and regenerators to be shared over many more connections. This allows for provisioning of connections with much superior Class of Service (CoS) vis-a-vis protection (resilience) while limiting the need for additional network resources. This can significantly enhance connection protection and service continuity while maintaining lower network cost.

5. ADDITIONAL TECHNOLOGY CHALLENGES AT OPTICAL LAYER FOR OBS

Power fluctuations[11–13] in optical burst switched networks arise because of the transparent, packet oriented switching that these networks use. With OBS, there are some physical layer issues pertaining to degradation of optical signals in other wavelengths when the power in one wavelength varies due to burst presence and absence. An OBS switch must assign output port bandwidth to bursts from multiple sources, which may be located at varying distances. So we encounter a variation of the near-far problem in which consecutive bursts propagate along a fiber with different power levels. In contrast, transparent circuit-switched optical networks enjoy greater power stability because they create point-to-point connections and maintain them over long periods of time.

As stated above, different bursts may have traversed different distances as they arrive at an OBS node. So when they arrive at the node in consideration, they may differ significantly from each other in their optical signal power measure. When optical bursts of disparate power levels are multiplexed together, they may cause wide power level fluctuations on the fiber and may cause serious signal quality degradation in other existing wavelength channels on the fiber. At least two of the important questions that we need to address are: (1) Is it possible to multiplex these bursts onto a common outgoing wavelength without causing any disruption of traffic in other wavelengths in the same fiber? (2) What can a receiver at the destination do to cope with successive bursts that may be widely varying in their power levels? Optical link engineering principles will need to be applied to examine and understand these issues in order to arrive at a feasible implementation of OBS. We briefly discuss several aspects of network architecture that are impacted by optical power fluctuation issues. They are the following: (1) optical receiver design, (2) optical amplifier placement, and (3) optical power equalization.

Optical Receiver Design: Optical receivers use a photodiode to convert an incoming optical signal into electronic form; the resulting electrical signal is used to form a bit-stream by comparing the signal energy in each bit period to a threshold that is chosen to minimize the individual bit error probability. Because of the near-far problem in OBS networks, each burst that arrives at a receiver can have a different power level. Thus a receiver with a fixed decision threshold will not be able to resolve the underlying bit stream with a minimum probability of error. This problem can be resolved by applying adaptive receiver techniques that were developed to enable optimal signal recovery in passive optical networks. The receiver measures the power level associated with each incoming burst and adjusts its decision threshold accordingly. This approach requires that each burst must carry a prefix that the receiver can use to set the decision threshold. Eldering[11] has shown that using the leading bit in the burst to set the decision threshold imposes a 3 dB penalty that is constant over a wide range of bit error rates (10^{-10} to 10^{-4}). Extending the training sequence to 8 bits will reduce the penalty to 0.51 dB, and increasing it further to 16 bits reduces the penalty to 0.28 dB. Thus a training sequence that is very small compared to the size of a typical burst is sufficient to significantly reduce the penalty imposed by burst power level fluctuations at the receiver.

Optical Amplifier Placement: Determining the optimal placement of in-line fiber amplifiers in an OBS network, where the peak power associated with each burst is variable, is a difficult task because not only does the optical signal power vary widely on each wavelength, but it also varies across the frequency range in the fiber. The result is that in-line fiber amplifiers are not likely to operate at desirable efficiency.

Optical Power Equalization (Effect on Other Wavelengths): For the reasons listed above, it is highly desirable to condition the set of the signals leaving an OBS switch on each fiber so that they have approximately the same power on each wavelength and this power level does not vary significantly over time. A simple form of equalization, which eliminates the dead times between consecutive bursts, was recently proposed by Jackel et al.[12] This approach, known as "Optical Burst Support," uses a saturated Semiconductor Optical Amplifier (SOA) in the optical feedback loop. Gaps between bursts are eliminated by using an offset wavelength that lies within the passband of the channel of interest. When the input power to the amplifier from the data stream falls to zero (i.e., during absence of a burst), the gains seen by the offset signal increases and the SOA lases at the offset frequency. This approach is similar to Automatic Gain Control (AGC) and Automatic Power Control (APC) techniques that are used to eliminate transients in WDM systems. For OBS networks, it appears that SOAs rather than EDFAs must be used to do this, because EDFAs cannot respond to changes in input power as rapidly as SOAs.

6. TRAFFIC SIMULATION AND PERFORMANCE RESULTS

OBS relies on statistical multiplexing for providing a more flexible and economical network. Hence it is necessary to develop a good understanding of the traffic models and simulate the OBS network to evaluate burst delays, losses, and connection QoS. Significant work has been reported in the literature on various performance aspects of OBS networks.[16–27,35] We have both simulation and analytical studies in progress[35] for quantifying trade-offs associated with OBS architecture and protocol choices. The burst routing and deflection routing algorithms are part of the focus of the simulations.[16] Bandwidth savings, economical usage of regenerators, router port cost reduction, and higher reach utilization of ULHR fibers are measures of comparison between OBS and existing core networks (i.e., GMPLS OTNs).

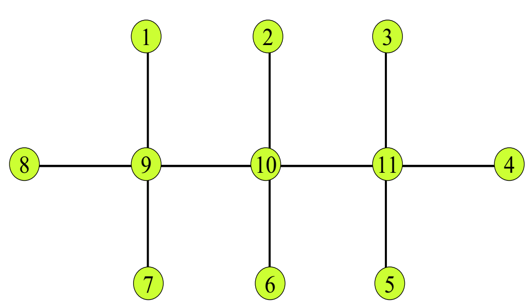

Figure 3. Simulation network topology

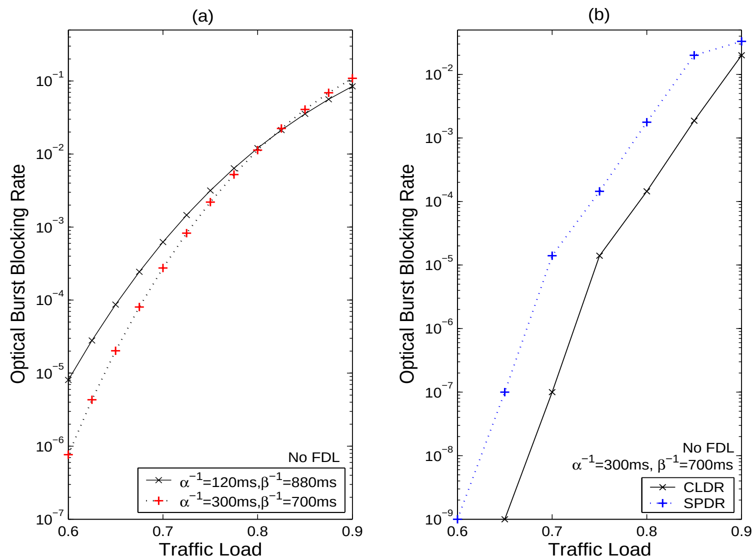

Figure 4. Burst blocking probability for an OBS multiplexer: (a) analytical and (b) simulations

Here we present some results from our performance studies to show the bandwidth efficiency and wavelength gain benefits of two OBS architectures: (1) with the use of Burst Wavelength Conversion (BWC) and (2) without the use of BWC. To show the results, we compare the OBS architectures with a conventional GMPLS architecture. Consider the simple mesh network shown in Figure 3. We assume that in the conventional GMPLS architecture, wavelength connections are setup between all pairs of edge nodes (i.e., nodes 1 through 8). Each wavelength connection is assumed to be filled up to some percentage traffic load value at an edge node, where packet buffering is done electronically. Such traffic within each GMPLS connection is assumed to come from multiple end-user sources that behave in an on-off manner. The on-off periods are on the order of hundreds of milliseconds (e.g., 300 ms and 700 ms). The peak bandwidth for each source within a GMPLS wavelength connection is assumed to be 100 Mbps. When OBS is used, it is assumed that IP packets are queued and bursts are filled at the edge nodes. Each burst is assumed to be of size 1Mbits, and would typically consist of many IP packets.

In Figure 4(a), we show the analytical prediction[16] of burst blocking probability at an OBS multiplexer as described above. We note that upwards of 60% channel utilization can be achieved on the egress wavelength for a blocking probability requirement of 10^{-5}. Corresponding simulation results[16] in an NSFnet network environment comparing two variants of deflection routing are shown in Figure 4(b). Deflection routing helps improve the burst

Table 2. Range of bandwidth efficiencies achievable due to OBS

(a) With BWC (at 70% egress bandwidth utilization) — (b) Without BWC (at 60% egress bandwidth utilization)

Statistical Multiplexing Gain											
	Average Optical Wavelength Fill						Average Optical Wavelength Fill				
Burst Overhead	10%	20%	30%	40%	50%	Burst Overhead	10%	20%	30%	40%	50%
0%	7.00	3.50	2.33	1.75	1.40	0%	3.00	3.00	2.00	1.50	1.20
5%	6.67	3.33	2.22	1.67	1.33	5%	3.00	2.86	1.90	1.43	1.14
10%	6.36	3.18	2.12	1.59	1.27	10%	3.00	2.73	1.82	1.36	1.09
15%	6.09	3.04	2.03	1.52	1.22	15%	3.00	2.61	1.74	1.30	1.04
20%	5.83	2.92	1.94	1.46	1.17	20%	3.00	2.50	1.67	1.25	1.00
25%	5.60	2.80	1.87	1.40	1.12	25%	3.00	2.40	1.60	1.20	0.96
30%	5.38	2.69	1.79	1.35	1.08	30%	3.00	2.31	1.54	1.15	0.92

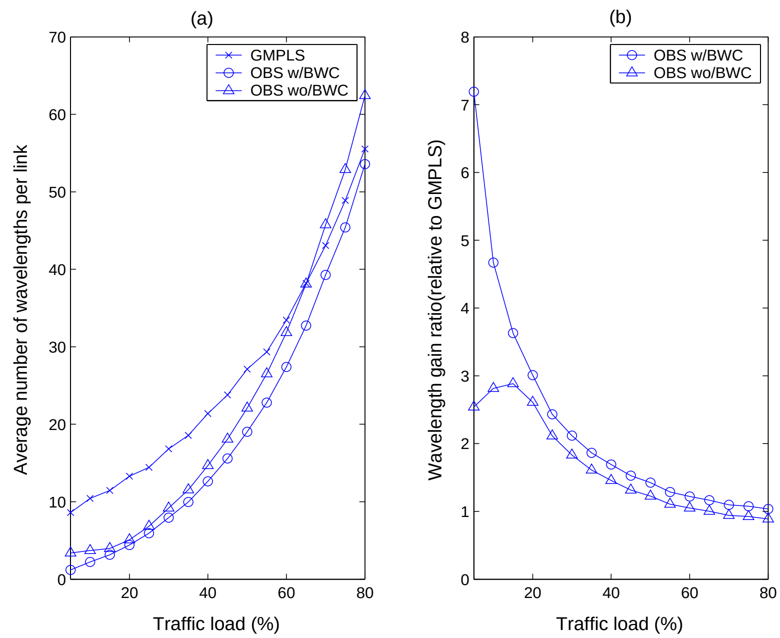

Figure 5. Comparison of (a) average wavelength usage per link and (b) gain ratios

blocking probability, and the wavelength channel utilization is better than 70% for the same blocking probability requirement of 10^{-5}. Details of the Shortest Path Deflection Routing (SPDR) and the Contention-based Deflection Routing (CLDR) can be found in the paper by Lee et al.[16]

Tables 2 (a) and (b) provide the estimated statistical bandwidth efficiencies due to OBS for a burst multiplexer for various values of ingress wavelength channel fill (input traffic load) and the burst overhead parameter. Tables 2 (a) and (b) are for the cases of OBS with and without BWC, respectively. The burst overhead is meant to include all overheads such as the guard-bands and other OBS switching overheads that affect the transmission bandwidth usage. The egress bandwidth utilizations (as a result of statistical multiplexing) are assumed to be 60% and 70% for OBS without BWC and with BWC, respectively (see Figures 4(a) and (b)). The case of OBS without BWC is assumed to have somewhat lower bandwidth utilization than the case with BWC because there are fewer wavelengths (one less than the number of ports at the OBS switch) that can be statistically multiplexed (see Figure 2). With fewer wavelengths on the input side of the switch that can be multiplexed into one output wavelength, the aggregate burst traffic is likely to be more correlated than the same for the case with BWC. As mentioned before, all this is based on a requirement of 10^{-5} on the probability of burst blocking and no FDL buffering. From Tables 2 (a) and (b), we note that the statistical multiplexing gain or wavelength channel gain can be quite high if the ingress wavelength channel fill is low and it decreases as the fill increases or the burst overhead increases.

Now we present some simulation results quantifying wavelength channel gain for the network topology shown in Figure 3. Figure 5 (a) shows a comparison of average wavelength usage per link for the cases of GMPLS network, OBS with BWC and OBS without BWC. In the GMPLS network, wavelength connections are assumed to be setup from edge-to-edge. Initially one wavelength connection is setup from each edge node to every other edge node. The number of these wavelength connections grows about 10% each year and the bandwidth fill within each wavelength also grows in 5% increments. For comparison, the same traffic to then assumed to be carried with OBS technology with or without BWC. At low to moderate wavelength fill (or traffic load with in each connection) values, OBS has significant advantage over GMPLS. As the fill increases to high values, the bandwidth usage by OBS catches up to that of GMPLS. The bandwidth usage for OBS can even exceed that for GMPLS due to burst overhead. Figure 5 (b) shows the bandwidth or wavelength channel gain ratios for OBS with/without BWC relative to GMPLS. The gain for the case with BWC can not exceed 3 for the topology of

Figure 3 because the maximum switch size is 4x4 fiber ports. The initial rise in the plot for the case without BWC can be explained by noting that the topology naturally is setup to combine traffic from three wavelengths into one wavelength (in the central nodes), but there is not enough traffic to show the 3:1 gain ratio. However, as traffic load increases slightly from 5% to 10% to 15%, the gain gets better as the 3:1 advantage is better utilized. Then as the traffic grows, the wavelengths channel gain ratio declines naturally for either case (with or without BWC). Based on these results and considering that traffic loads in wavelength channels are typically low to moderate (10% to 30% range), it may be noted that OBS with BWC has significant advantage and should be pursued for implementation.

7. CONCLUDING REMARKS

We have highlighted the benefits of OBS and also tried to balance the same with recognition of potential technological challenges. The burst power management and burst integrity issues need continued focus on part the technical community to solve those problems ingenuously. As for the statistical multiplexing, traffic and QoS management, resiliency and resource savings, we feel that OBS holds significant promise when compared to what can be done with existing optical transport networks. Significant progress is being made with regard to developing QoS management, OBS traffic engineering methods, and mechanisms for congestion control and connection protection and restoration. Once the technological hurdles are overcome for building the optical burst switching fabrics and optical quality management for burst transport, then a clearer path to deployment of OBS networks will begin to emerge. The use of fast tunable lasers for Burst Wavelength Conversion (BWC) is another important technology advancement that can significantly benefit OBS. We have reported some interesting quantitative results related to bandwidth savings in this paper, comparing GMPLS and OBS with/without BWC. A more detailed technical report is currently in preparation.[35]

REFERENCES

1. D. Griffith and S. K. Lee, "A 1+1 Protection Architecture for Optical Burst Switched Networks," to appear in *IEEE Journal on Selected Areas in Communications*.
2. *IEEE Communications Magazine*, Special issue on Packet-Oriented Photonic Networks, September 2002.
3. C. Qiao, and M. Yoo, "Optical Burst Switching (OBS) - A New Paradigm for an Optical Internet," *Journal of High Speed Networks*, vol. 8, no. 1, pp. 69-84, January 1999.
4. S. Verma, H. Chaskar, and R. Ravikanth, "Optical Burst Switching: A Viable Solution for Terabit IP Backbone", *IEEE Network Magazine*, vol. 14, no. 6 , pp. 48 -53, November/December 2000.
5. H.M. Chaskar, S. Verma, and R. Ravikanth, "Robust Transport of IP Traffic over WDM Using Optical Burst Switching", *Optical Network Magazine*, vol. 3, no. 4, pp. 47-60, July/August 2002.
6. W.T. Anderson et al., "The MONET project - A final report," *Journal of Lightwave Technology*, vol. 18, no. 12, pp. 1988-2009, December 2000.
7. B. Mason et al., "Design of Sampled Grating DBR Lasers with Integrated Semiconductor Optical Amplifiers," *IEEE Photonics Technology Letters*, vol. 12, no. 7, July 2000.
8. M.C. Larson and G.A. Fish, "Monolithic widely-tunable samples-grating DBR lasers," http://www.agility.com/technology/journal.phtml (2001).
9. F.J. Duarte (Ed.), *Tunable Lasers Handbook* (Academic, New York, 1995)
10. F.J. Duarte, Tunable Lasers Web Page, http://www.opticsjournal.com/tunablelasers.htm
11. Eldering, C. A., "Theoretical Determination of Sensitivity Penalty for Burst Mode Fiber Optic Receivers," *Journal of Lightwave Technology*, vol. 11, no. 12, pp. 2145-2149, December 1993.
12. Jackel, J. L., Banwell, T. C., McNown, S. R., and Perreault, J. A., "All-Optical Burst Support for Optical Packets," *Proceedings of the 27th European Conference on Optical Communications (ECOC'01–Amsterdam)*, pp. 368-369.
13. Nizhizawa, H., Yamada, Y., Shibata, Y., and Habara, K., "10-Gb/s optical DPSK packet receiver proof against large power fluctuations," *IEEE Photonics Technology Letters*, vol. 11, no. 6, pp. 733-735, June 1999.
14. "Optical Phased Array Technology for High-Speed Switching", White Paper, http://www.chiaro.com/pdf/CHI100_OPA_1.pdf , Chiaro Networks, 2002.

15. "64x64 Fast Optical Switching Module," White Paper, http://www.chiaro.com.
16. S.K. Lee, K. Sriram, H.S. Kim, and J.S. Song, "Contention-Based Limited Deflection Routing Protocol in Optical Burst-Switched Networks," to appear in part in *Proc. of the IEEE Globecom* 2003; submitted to *IEEE JSAC*, special series on Optical Networks.
17. C. Gauger, "Contention Resolution in Optical Burst Switching Networks", Advanced Infrastructures for Photonic Networks: WG 2 Intermediate Report, http://www.ikr.uni-stuttgart.de/Content Publications/Archive/Ga_COST266WG2_34734.ps.gz, 2002.
18. M. Yoo, C. Qiao, and S. Dixit, "A Comparative Study of Contention Resolution Policies in Optical Burst Switched WDM Networks", International Conference on Terabit Optical Networking: Architecture, Control and Management Issues, *Proceedings of SPIE*, vol. 4213, pp. 124-135, Boston, November, 2000.
19. C. Gauger, "Performance of Converter Pools for Contention Resolution in Optical Burst Switching", *Proceedings of the SPIE Optical Networking and Communications Conference (OptiComm 2002)*, Boston, pp. 109-117, July 2002.
20. C-F. Hsu, T-L Liu and F-F Huang, "Performance Analysis of Deflection Routing in Optical Burst-Switched Networks", IEEE Proceedings INFOCOM'02, vol. 1, pp. 66-73, NewYork, USA, June 2002.
21. S. Kim, N. Kim, and M. Kang, "Contention Resolution for Optical Burst Switching Networks Using Alternative Routing", *IEEE Proceedings of International Conference of Communications (ICC'02)*, vol. 5, pp. 2678-2681, NewYork, USA, Apr/May. 2002.
22. X. Wang, H. Morikawa, and T. Aoyama, "Burst Optical Deflection Routing Protocol for Wavelength Routing WDM Networks", *Optical Networks Magazine*, pp. 12-19, November/December 2002.
23. C.Y. Li et al, "Deflection Routing in Slotted self-routing Networks with Arbitrary Topology", *IEEE Proceedings ICC'02*, vol. 5, pp. 2781-2785, NewYork, USA, April/May 2002.
24. V. Vokkarane and J. Jue, "Prioritized Routing and Burst Segmentation for QoS in Optical Burst-Switched Networks", *Proc. Optical Fiber Communication Conference (OFC) 2002*, pp. 221-222, March 2002.
25. J. Y. Wei, J. L. Pastor, R. S. Ramamurthy, and Y. Tsai, "Just-In-Time Optical Burst Switching for Multi-wavelength Networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 18. no. 12, pp. 2019-2037, December 2000.
26. I. Baldine, George N. Rouskas, H.Perros, and D. Stevenson, "Jumpstart: a Just-in-Time Signaling Architecture for WDM Burst-Switched Networks", *IEEE Communications Magazine*, vol. 40, no. 2, pp. 82-89, February 2002.
27. C. Gauger, K. Dolzer, and M. Scharf, "Reservation strategies for FDL buffers in OBS networks", Report, IND, University of Stuttgart, 2001
28. R. Ramaswami and K. N. Sivarajan, *Optical Networks - A Practical Perspective*, Second edition, Morgan Kaufmann Publishers, pp.649, 2002.
29. R. Nagarajan, M.A. Qureshi, and Y.T. Wang, "A Packet 1+1 Path Protection Service for MPLS Networks," Internet Draft, draft-nagarajan-ccamp-mpls-packet-protection-00.txt , March 2002.
30. K. Sriram and W. Whitt, "Characterizing Superposition Arrival Processes in Packet Multiplexers for Voice and Data," *I*EEE Journal on Selected Areas in Commun., vol. SAC-4, no. 6, pp. 833-846, September 1986.
31. J. White, M. Zukerman, and H. Vu, "A Framework for Optical Burst Switching Network Design," *I*EEE Communications Letters, vol. 6, no. 6, pp. 268-270, June 2002.
32. A. Ge, F. Callegati, and L.S. Tamil, "On Optical Burst Switching and Self-Similar Traffic," *I*EEE Communications Letters, vol. 4, no. 3, pp. 98-100, March 2000.
33. D.B. Liu, and M.T. Liu, "Differentiated Services and Scheduling Scheme in Optical Burst-Switched WDM Networks," *Proceedings of the 10th IEEE International Conference on Networks (ICON)*, pp. 23-27, 27-30 Aug. 2002.
34. V. Vokkarane, Q. Zhang, J.P. Jue, and B. Chen, "Generalized Burst Assembly and Scheduling Techniques for QoS Support in Optical Burst-Switched Networks," *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '02)*, vol. 3, pp. 2747–2751, Nov. 17-21, 2002.
35. K. Sriram, D. W. Griffith, S.K. Lee, and N.T. Golmie, "Optical Burst Switching: Benefits and Challenges," Technical Report (Draft), National Institute of Standards and Technology (NIST), 2003.